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The observational evidence for long-range propagation of high-frequency radio signals began to accumulate in 1926 when transatlantic communication links had been established. In 1927, signals were detected that had propagated over large distances or circled the earth with little attenuation. Long-range and round-the-world (RTW) signals showed preferred periods of occurrence. Relatively high angles of incidence (20 relative to the horizontal) of such signals at the receiver, paired with low attenuation, ruled out conventional multi-hop propagation. An ionospheric refractive index boundary was postulated

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along which the signal propagates in a glancing-incidence low-loss mode.

The transmission path of observed long-delayed signals, originating from artificial earth satellites, was found to be located in the twilight zone. Experiments using ground-based transmissions confirmed the role of ionospheric absorption and tilts for the occurrence of long-range and RTW signals. Detailed explanations for ionospheric ducting were provided using several theoretical concepts and analyses. The μr (refractive index times geocentric distance) - diagram was used for the study of ray propagation in a spherically stratified multi-layered model ionosphere depicting characteristics of the ground-detached glancing-incidence mode. The potential-well analysis was applied to an inhomogeneous, slowly varying ionosphere. Numerical ray-tracing computations were made using model ionospheres with horizontal gradients. Ionospheric models were used to predict global properties of ionospheric wave channels. The role of scattering from natural and artificially induced ionospheric irregularities in long-range ionospheric ducting was investigated.

Preface

In 1976, the concept emerged in the Propagation Branch of the Electromagnetic Sciences Division to investigate the possibility of using ionospheric ducting channels for low-loss, long-range propagation. This concept appeared attractive because of recent advances in ionospheric sounding systems and the development and use of radio frequency heaters for ionospheric modification. From such modification experiments, it was recognized that artificially produced ionospheric irregularities could be utilized to inject, by way of scatter, radio energy from the ground into prevailing ionospheric ducts. In these ducts, this energy could propagate with little attenuation over long distances, thus giving this technique desirable attributes for radio communication. For this reason, it was of interest to review here the developments over the past fifty years pertaining to studies of long-range and round-the-world propagation involving ionospheric ducts.

The author presented this review paper to the commission 'Ionospheric Radio' during the 19th General Assembly of the International Union of Radio Science, held at the Helsinki University of Technology, Finland, from 31 July to 8 August 1978. Earlier this year he had been invited by the international chairman to convene a session on "Long-Range HF Ionospheric Ducting" and to present this review.

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1. INTRODUCTION

Radio communication over large distances has been for almost 80 years an integral part of man's engineering efforts. Following the discovery of the ionosphere in 1925, it was noted that radio signals in the high-frequency band could circle the earth and be detected as a result of low signal losses encountered along the path of propagation. These observations established the usefulness of the conducting properties of the 'electrified' layers of the upper atmosphere for propagation of radio signals over distances exceeding by far those that could be associated with ground wave propagation along the surface of the earth. As transatlantic communication links were established, it was noted that the long-range radio signals were not persistently available for satisfactory communication. These observations were associated with the varying properties of the ionospheric layers and led to extensive experimental and theoretical studies of ionospheric structure and behavior as well as of high-frequency propagation characteristics. Over the years, general interest in the use of high-frequency signals for long-range propagation and communication decreased, particularly since artificial earth satellites became available for use as repeaters in earth-space-earth radio links. Recently, however, interest in high-frequency propagation by way of ionospheric channels was revived; perhaps as a result of our improved but yet insufficient knowledge of the spatial properties of ionospheric structure extending over the entire globe. This renewed interest

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provided the incentive for reviewing in this report, the pertinent developments in the field during the last fifty years. It is hoped, thereby, to aid the perception of future uses and facilitate better understanding of these modes of propagation in terms of availability, stability, and so on, including their relationship to global ionospheric structure and processes.

2. EARLY MEASUREMENTS

In 1927, communication was established between a short-wave (18.55 MHz) transmitting station in the United States and a Transradio receiving station in Germany. The occurrence of a doubled-signal was observed following a short time later than the principal signal. The doubled-signal (ghost signal) was attributed to a propagation path encircling the earth in the other direction than of the principal signal causing—at times—interference.[1] Round-the-world (RTW) signals were also observed with a delay of 0.135 to 0.138 of a second. Estimates of the height at which the ray, associated with the propagating signal may travel, however, were unreliable because of uncertainties in electron density and 'wave' velocity.[2,3] Interference considerations associated with spurious echo signals led to distinctions between RTW and ground-backscatter signals when it was ascertained that the undesirable influence of the former on the communication signal could be taken care of by directive receiving systems. For short-delay spurious echo signals, attributed to ground-backscatter, such directive receiving systems were thought not to be of much advantage.[4] The authors[4] also concluded that RTW signals, originating from European stations, were generally observable in the Eastern United States during the fall and early winter months and during the middle of the morning hours if they arrived from the southwesterly direction. They predicted that, for any given pair of stations, RTW signals must make most of their night transit in the summer hemisphere in order to be detectable.

Field strength curves of transatlantic short-wave transmissions, recorded over half a sunspot cycle, included those of "echoes" observed between station pairs (for example, Shanghai-Beelitz or New York-Berlin). "Echoes" along the short and long links of the great-circle paths (GCP) between such stations were observed.

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1. Quäck, E. (1927a) Propagation of short waves around the earth, Proc. IRE **15**:341-345.
2. Quäck, E. (1927b) Further communication on the propagation of short-waves, Proc. IRE **15**:1065-1068.
3. Eckersley, T.L. (1927) Short-wave wireless telegraphy, J. Inst. Elec. Engrs. (London) **65**:600-644.
4. Hoyt Taylor, A., and Young, L.C. (1928) Studies of high-frequency radio wave propagation, Proc. IRE **16**:561-578.

Their occurrence was more frequent during solar maximum (f~ 20 MHz) than minimum (f~ 15 MHz). Moreover, if the short-link New York-Berlin path was in daylight, the long-link "echoes" traveling into and through hemispherical darkness were more prevalent and vice versa.[5]

The occurrence of a single or multiple RTW echo was thought of as allowing two interpretations.[6] The conventional multi-hop propagation, involving many bounces between the earth and ionosphere, appeared less likely on account of the claim that relatively large elevation angles at reception had been observed(about 20° above the horizontal), differences in RTW signals propagating over land- or sea-paths had not been detected, and RTW echo-delay time appeared to be frequency- and time-invariant—suggesting no frequency dispersion. The second interpretation introduced the concept of a "Gleitwelle."[6] Rays were thought of entering the F layer at a limiting angle such that the 'refracted' ray advances in the direction of the layer boundary while energy is leaking out at that angle.

Subsequent measurements of incidence angles for 17.78 MHz signals, originating from Bound Brook in the United States and received in Germany[7] seemed to corroborate Schmidt's[6] "Gleitwellen" mechanism. The measurements showed that for larger arrival angles (about 23° above the horizontal) larger field strengths were recorded that were comparable to those received from European transmitters. For smaller arrival angles, weaker signals were recorded that suggested a conventional multi-hop mechanism. Some of these observations and interpretations were re-examined and further measurements between 1941 and 1944 corroborated these earlier conclusions. More accurate RTW delay times of telegraphy signals were obtained (0. 137788 msec), some of which encircled the earth several times. The signal strength peaked when propagation took place along the twilight belt or terminator.[8] It was also confirmed that signal distortion diminished for longer propagation paths for which angles of incidence with respect to the horizontal were found to be about 20°, while those for multi-hop propagation between ionosphere and ground, were expected to be approximately 3°. The seasonal dependence of useful reception of 7 MHz radio signals between Europe and Australia showed that successful propagation lasting for 2 to 4 hr occurred earlier (5 to 8 UT) during northern summer and later (7 to 10 UT) during northern winter.[9] Chordal-type propagation involving tilt-supported modes was

5. Mögel, H. (1934) Kurzwellenerfahrungen im drahtlosen Überseeverkehr von 1926 - 1934, Telefunken-Z. **15**(No. 67):23-39.

6. Schmidt, O. (1936) Neue Erklärung des Kurzwellenumlaufes um die Erde, Z. Tech. Phys. **17**(No. 11):443-446.

7. Schüttlöffel, E., and Vogt, G. (1940) Die Einfallswinkel der Kurzwellenstrahlung im Überseeverkehr (Referat.), Hochfrequenztech. Elektroakus. **56**(Nos. 4& 5):123-125.

8. Hess, H.A. (1946) Untersuchungen an Kurzwellen - Echosignalen, Z. Naturforsch. **1**(No. 9):499-505.

9. Albrecht, H.J. (1957) Investigations on great-circle propagation between eastern Australia and western Europe, Geofis. Pura Appl. **38**:169-180.

inferred from a study of amplitude variations of short-wave broadcasts over long paths crossing the magnetic equator. This type of propagation can involve two or more successive reflections from the F layer without intermediate reflection from the ground. If these and conventional multiple earth-ionosphere reflection modes are simultaneously present in comparable strength, and the electrical path length of one varies with respect to the other, the observed interference effects can be used to postulate the presence of chordal-type propagation modes.[10] Assuming the presence of chordal propagation, an empirical equation for more successful prediction of path loss was derived, taking into account the absence of ground reflections and focusing due to concave layers, but not ionospheric absorption and antipodal focusing.[11]

Unusual observations of satellite-to-ground signal receptions at 40 MHz were reported involving long-range propagation during morning and evening passes of the first artificial satellite when at the antipode of the receiving station.[12] From similar observations made at 20 MHz, it was surmised that the mode of propagation for antipodal reception involved penetration of the F layer followed by internal ionospheric reflection. The direction of arrival remained unchanged throughout each antipodal passage. Ionospheric tilt prior to local sunset appeared to provide a propagation path and a narrow azimuth of arrival of the signal.[13] Other ground-to-ground (37 MHz) observations revealed that for the Gibraltar-United Kingdom link, RTW signals were received four to five hours after local sunrise, representing a considerable displacement of the twilight belt from the great-circle path followed by the circulating signal. For satellite-to-ground (20 MHz) observations, it was postulated that the mechanism for RTW propagation is associated with reflections at glancing angles of incidence which are confined solely to the ionosphere.[14]

Studies of frequency dependence of RTW time delays and pulse dispersion showed that they were both functions of frequency. Measured minimum time delays were compared with theoretical delay predictions and matched those obtained for takeoff angles ranging from 2 to 6 degrees. The evidence of the presence of a multiplicity of RTW propagation modes was suggested.[15]

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10. Yeh, K.C., and Villard, Jr., O.G. (1958) A new type of fading observable on high-frequency radio transmissions propagated over paths crossing the magnetic equator, Proc. IRE **46**:1968-1970.

11. Albrecht, H.J. (1959) Further studies on the chordal-hop theory of ionospheric long-range propagation, Arch. Meteorol. Geophys. Bioklimatol. **11**(No. 1):84-92.

12. Wells, H.W. (1958) Unusual propagation at 40 MC from the USSR satellite, Proc. IRE **46**:610.

13. Garriott, O.K., and Villard, Jr., O.G. (1958) Antipodal reception of Sputnik III, Proc. IRE **46**:1950.

14. Isted, G.A. (1958) Round-the-world echoes, Marconi Rev. **21**(No. 131):173-183.

15. Fenwick, R.B., and Villard, Jr., O.G. (1963) Measurements of the frequency dependence of round-the-world HF pulse time delays and dispersions, Proc. IRE **51**(No. 9):1240-1241.

Further confirmation was obtained that RTW propagation is not confined to the "twilight zone" when it was observed that propagation orthogonally to this zone is also possible. RTW propagation modes were also found to be qualitatively predictable by use of world maps of foF2 and absorption, and by proper consideration of the effects of ionospheric tilts.[16,17] The "tilt mode" required the transmission point to be in the daylight hemisphere. The ionosphere-ionosphere mode appeared prevalent in the dark hemisphere while the earth-ionosphere-earth hop mode prevailed in the sunlit hemisphere. It was also noted that electromagnetic energy in the tilt-supported mode could pass overhead, being undetectable on the ground at sites located in the dark hemisphere, and yet detectable at a site in the daylight hemisphere.[18] In a study of antipodal and one and one-half times around-the-world signals, a propagation model incorporating ionosphere-ionosphere reflections in the night areas of the world appeared to explain the observed phenomena. For a one-month radio experiment conducted between Texas and aboard a ship in the Indian Ocean, variations of the average maximum observed frequency of the 3/2 RTW mode were obtained ranging from 12 to 18 MHz over 3 hr around twilight.[19] Antipodal radio focusing was also studied by calculating for a smooth earth and ionosphere the power available near the antipodal point when the ionosphere is situated eccentrically about the earth. It was surmised, however, that ducting under the assumption of a smoothly varying medium may be limited to short paths only. This assumption appeared unlikely to hold for ducting over large distances. The scattering properties of the ionosphere associated with the presence of ionospheric irregularities, their distribution with height and occurrence with size had to be invoked.[20]

Since horizontal gradients in the distribution of electron density govern the radio wave trajectories and influence maximum usable frequencies, hop distances, angles of arrival, and can lead to ducting in elevated ionospheric channels, the planetary distribution of longitudinal gradients of critical F2-layer frequency and their diurnal

16. Fenwick, R.B. (1963) Round-the-World High-Frequency Propagation, Tech. Rep. No. 71, Stanford Electronics Laboratories, Stanford University, Stanford, CA, April 1963; AD404303.

17. Fenwick, R.B. (1966) Sweep-Frequency, Spaced-Station Measurements of Round-the-World HF Propagation, Tech. Rep. No. 122, Stanford Electronics Laboratories, Stanford University, Stanford, CA, June 1966; AD801701L.

18. Fenwick, R.B., and Villard, Jr., O.G. (1963) A test of the importance of ionosphere-ionosphere reflections in long-distance and around-the-world high-frequency propagation, J. Geophys. Res. **68**(No. 20):5659-5666.

19. Banks, P.M. (1965) Measurements of antipodal high-frequency radio signals, J. Geophys. Res. **70**(No. 3):625-638.

20. Whale, H.A. (1969) Effects of Ionospheric Scattering on Very-Long Distance Radio Communications, 171 pp., Plenum, New York.

seasonal, and solar-cycle variations were examined.[21] It was found that at middle latitudes morning-maxima of these gradients appeared in winter, while in equatorial regions, they appeared throughout the year. During low solar activity, the gradients increased with proximity to the equator in winter and in summer. An increase in solar activity was associated with an increase in these horizontal gradients. This increase was more pronounced in winter than in summer. Gradients were found to be about 0.2 MHz per 100 km horizontal distance.

3. MORE RECENT MEASUREMENTS

Previous limitations of equipment and technique have been reduced significantly by the development of the sweep-frequency continuous-wave sounding technique applied to RTW propagation. This resulted in the observation of a fine structure in single-orbit RTW ionograms over the long path between a transmitter in Arkansas and a receiver in California. Such a fine-structure resulted from the signal having traveled a number of paths of different lengths causing delay spreads of about 2 milliseconds. The number of paths decreased with increasing frequency. Hook-like features were also noted in the RTW ionograms that showed a likeness to the MUF "nose" feature seen on oblique ionograms taken over shorter path.[22]

Further evidence for the glancing-incidence hop mechanism of RTW propagation over the Moscow-Molodezhnaya (Antarctica) link (13,700 km, 26,300 km), gathered during a 1967-measurement program, was deduced when the operating frequency of the available band (4.5 to 23 MHz) exceeded the MUF of the ray tangent to the earth. The most probable value for RTW signal travel time measured at Molodezhnaya was 0.1382 second.[23] RTW signals were most prevalent during the equinoxes.

Characteristics of circumterrestrial (RTW) signals were also observed between June and July 1973 over Cuba-USSR transmission paths on frequencies 12.2, 14.9, and 16.2 MHz, but not in September and October, and never at 10.7 MHz. The occurrence of RTW signals appeared to coincide with enhanced oblique backscatter activity suggesting that scattering by ionospheric inhomogeneities may play a role in trapping electromagnetic energy in the ionospheric wave duct.[24]

21. Kovalevskaya, Ye. M. (1967) Horizontal gradients of critical F2-layer frequency associated with local time, Geomagn. Aeron. 7(No. 4):588-590.

22. Bubenik, D.M., Fraser-Smith, A.C., Sweeney, Jr., L.E., and Villard, Jr., O.G. (1970) Observations of Fine Structure in HF Radio Signals Propagated Around the World, Tech. Rep. No. 164, Stanford Electronics Laboratories, Stanford University, Stanford, CA, Dec 1970; AD72170.

23. Golyan, S.F., and Shlionskiy, Sh. G. (1971) Propagation of circumterrestrial echo signals, Geomagn. Aeron. 11(No. 1):76-79.

24. Berdeyans, D., Bocharov, V.I., Lobachevskiy, L.A., Martinez, R., Suares, H., and Tushentsova, I.A. (1975) Types of propagation of radio waves of the decameter range, according to observations by the OBS method on Cuba-Soviet Union paths, Geomagn. Aeron. 15(No. 1):135-137.

The propagation conditions of HF signals over the short and long great-circle path between Wertachtal, Germany and Melbourne revealed again that stronger signals may be received over the longer (24,000 km) rather than the shorter (16,000 km) great-circle path, if the former extends over the night-hemisphere. Corrections to C.C.I.R.-prediction methods were proposed in which ground-reflections were eliminated for the chordal modes and an antipodal focusing gain was introduced.[25]

4. COMPUTATIONAL STUDIES

A general expression was derived describing the refraction of radio waves passing through a spherical ionized layer. Critical ionospheric height levels were identified at which perpetual propagation around the earth was found to be theoretically possible.[26] A raytracing technique was used for examining the possibility of long-range one-hop propagation by way of the F_1 and F_2 layers without invoking horizontal ionization gradients. It was found that one-hop propagation may occur over 7500 km paths in temperate regions and over 10,000 km in equatorial regions. Measurements over the 5600 km circuit between Ottawa, Canada and The Hague, Netherlands showed that one-hop propagation regularly occurred during the summer daytime.[27] It was proposed that divergence of the Pedersen ray may be reduced if diffusion is invoked resulting in an increase of the layer width in a parabolic approximation, making this mode of propagation more likely.[28]

Computations of ray paths in a spherically layered ionosphere with and without the presence of horizontal ionization gradients showed that chordal- and hop-mechanisms may be involved in the propagation over long distances with radiating sources on the ground or at ionospheric heights.[29, 30, 31, 32, 33]

In a numerical study, the influence of the depth of the ionization valley between the E and F layers and the horizontal ionization gradients on the efficiency of HF ducting was determined for two- and three-dimensional ionospheric models neglecting collisions.[34] The latter model was used for synthesizing forward and backscatter ionograms from ray computations. An example of a synthesized backscatter ionogram, illustrated in Figure 1, shows that for selected frequencies and take-off angles long delays as well as escaping rays characterize the effect of negative horizontal gradients on the advancing ray trajectory.

(Because of the large number of references cited above, they will not be listed here. See References, page 19, for References 25 through 34.)

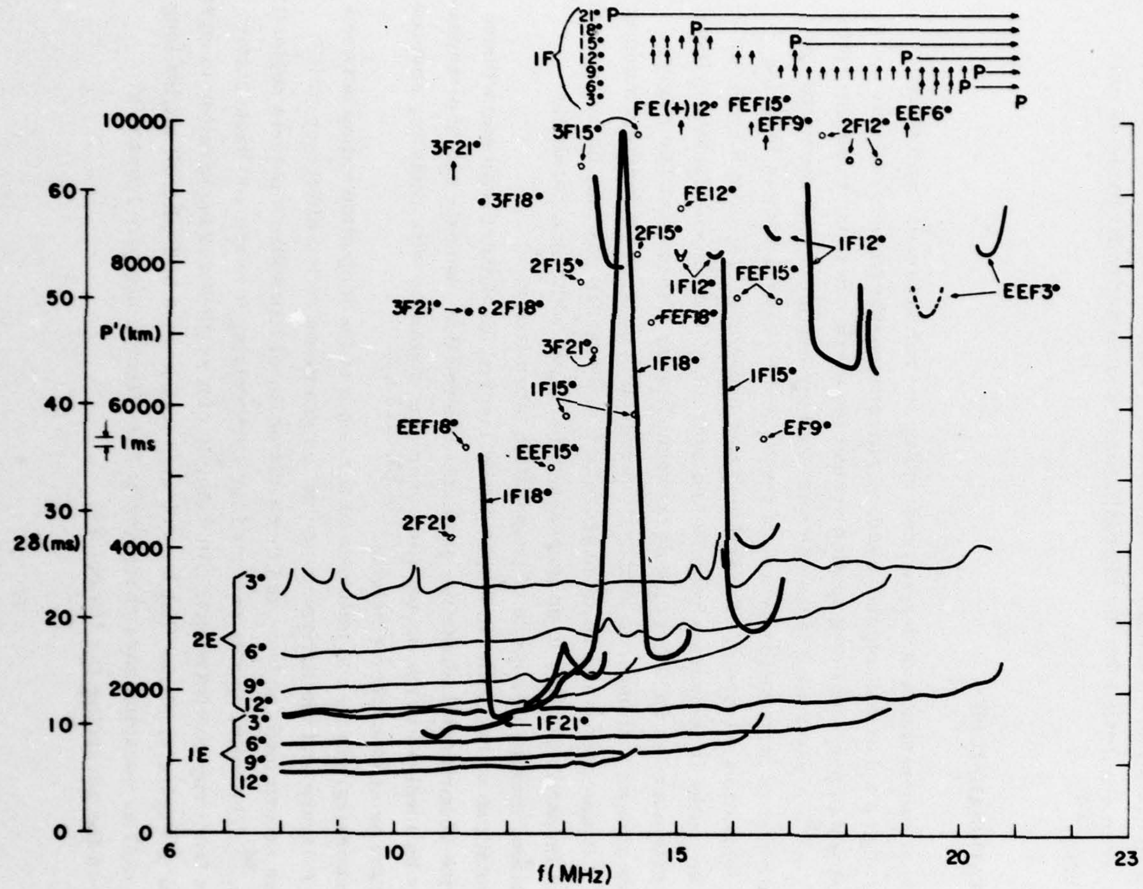

Figure 1. Synthesized Oblique Backscatter Ionogram. U.S. to U.K.: Polar model (1976), 15 April 1977, 1800 UT, Z = 50, Kp = 2, ordinary ray, no collisions, $\Delta\theta = 3°$

To determine those ionospheric regions that are capable of "capturing" rays which emanate from a source of radiation only to be ducted in ionospheric radio waveguides, use was made of the concept of the modified refractive index[35] and the μr function in which μ is the ionosphere refractive index and r is the geocentric distance.[36] For a particular operating frequency and for a chosen ionosphere profile, the μr-curve, plotted as a function of geocentric distance, was shown to define uniquely the altitude limits between which any given ray is confined. In a spherically symmetric, geocentric, lossless iosotropic ionosphere any particular duct may be completely characterized by an appropriately chosen marginal ray. The apogee and perigee altitudes of this ray define the altitude boundaries of the duct, and the absolute value of its elevation angle at any altitude defines the angular width of the duct at that altitude. It was noted that to make the ground-detached mode available to ground-based radio terminals, some mode-coupling mechanism must be provided. In practice, favorably placed ionospheric tilts frequently effected the coupling of modes. A less fortuitous coupling mechanism was proposed involving reflections from ionospheric ionization irregularities such as meteor trails and field-aligned columns.[37] Thus, under the assumptions made about the ionosphere for which the μr-curve was computed, the latter can be said to reveal the presence of ducting channels that are, however, not accessible to rays originating from outside the duct, such as from ground-based terminals.

In an approach that was recognized to serve a similar purpose as the μr-curve, the equation defining the propagation of waves in a spherically symmetric layer was recognized as being equivalent to the Schrödinger equation for a particle moving in a potential field. An analysis was conducted of RTW propagation of waves in an inhomogeneous ionosphere with day-to-night transitions, using the method of approximation of the adiabatic invariant. It was concluded that using this analysis, a special ionospheric ducting channel arises, in which the wave absorption is very small (20 dB). Depending on the choice of the ionospheric model, waves with frequencies between 12 and 25 MHz may propagate in elevated ionospheric channels. The possibility was suggested that a non-linear defocusing mechanism may lead to trapping in ionospheric channels of strong radio waves that are launched from the ground.[38]

35. Danilin, V. A. (1967) Ionospheric waveguide channels for distant radio communication below the maximum of the F2 layer, Cosmic Res. **5**(No. 2):199-206.

36. Shlionskiy, Sh. G. (1968) Determination of the extreme levels of the rn(r) function and MUF under various ionospheric conditions, Geomagn. Aeron. **8**(No. 2):295-297.

37. Bubenik, D. M. (1976) The Combined Effects of Refraction and Coherent Scattering by Columnar Ionization Density Irregularities in Ionospheric Radio Propagation, PhD thesis, 1976, Stanford University, Stanford, CA.

38. Gurevich, A. V. (1971) Effect of non-linearity on the generation of signals circling the earth, Geomagn. Aeron. **11**(No. 6):810-817.

The global characteristics of waveguides in an inhomogeneous ionosphere were studied in the adiabatic approximation. Not only the vertical but also the horizontal inhomogeneous structure of the ionosphere was considered. Assuming a slowly varying ionosphere along the ray path, horizontal inhomogeneities in the ionosphere had to vary slowly so that the adiabatic invariant for ray oscillations in the vertical direction was conserved. This condition was believed to be violated in the region of the terminator where horizontal ionization gradients are usually very large. The use of the adiabatic approximation, though limited, helped to clearly identify ionospheric waveguides that trap the wave in the channel, the escape of waves from the waveguide, and the transition from one guide to another.[39]

The global properties of ionospheric wave ducts in the HF range were further investigated in the adiabatic approximation using an analytical model of the ionosphere. The model was constructed for quiet equinoctial conditions during solar activity minimum. The properties of ducts occurring in various ionospheric regions, such as D, E, FE, and F region ducts, were investigated without considering absorption and scatter of radio waves. Together with the corresponding values of the adiabatic invariant, the total volume of the various ducts, their minimum and maximum heights and a value for the adiabatic invariant of the ray emitted from the earth were obtained. The model was used to predict the distribution of the boundaries of ducting channels along a noon-midnight meridian for $f = 15$ MHz. Hop propagation through the E and F ducts was possible only for the noon meridian. The E duct disappeared at night and the F (or FE) duct appeared separated from the earth. The FE duct had a minimum volume near the poles and at midlatitudes during daytime. Because of a lowering of the height of the F layer maximum, the FE duct was found narrower at polar latitudes such that RTW propagation through the F duct would be difficult.[40]

The uncertainty of successfully injecting radio energy into elevated ionospheric ducts from the ground by way of naturally occurring irregularities, led to the thought of artifically producing inhomogeneities in the ionosphere using powerful radio waves. The scattering of radio waves by artificially created inhomogeneities was recognized to be useful for injecting radio energy into a duct from the ground and to draw the trapped energy from the duct. The scattering geometry was examined for field-aligned irregularities. It was assumed that rays are already trapped in the ionospheric wave duct and propagate in a nearly horizontal direction. Regions on the ground were identified where separated transmitter and receiver would have to be

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located to observe RTW signals by way of scattering from artificially induced field-aligned irregularities.[41]

5. CONCLUDING REMARKS

The study of long-range ducting in ionospheric channels is clearly aimed at utilizing the ionosphere to the utmost. The development in the field over the last 50 years revealed the emergence of new concepts and measurement techniques, provided improved ionospheric models more representative of actual conditions, brought about considerable advances in computational capability for tracing rays through inhomogeneous ionospheres, and introduced the era of radio-frequency modification of the ionosphere which linked plasma physics with ionospheric research. The sensitive FM/CW sounding technique is expected to provide further information on the fine structure and stability of ducted signals. Combining faster computational techniques with the use of FM/CW links operating over shorter than RTW paths, it may be possible to also enhance diagnosing ducted modes by means of oblique and backscatter ionograms.

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